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ELECTRICAL PROTECTION OF A LOW-CURRENT SUPERCONDUCTING MAGNET

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1. Abstract

This note describes primarily the electrical protection of a prototype low-current ($\sim$ 200A) superconducting magnet, type 6SD48, installation #BH716X, installed in the Proton-West beam line. The magnet protection consists of lead over-voltage detection, magnet quench detection, energy dump resistors, He level interlocks and a heater power supply. Several other protective interlocks have been installed in the magnet power supply to permit safe operation of the equipment.

Attached drawings give detailed information about the used circuitry.

2. Description of the superconducting magnet 6SD48

The magnet[1)] is 4-feet long and has a 6" cold bore. The windings are made by connecting the 15 individually-insulated strands of a superconducting cable in series. Thin, stainless steel strips are non-inductively wound in alongside some coil windings. These strips are used as heating elements and are supplied from an external heater power supply. Supplying current to the strips promotes quenching of the whole magnet, after a spontaneous quench has been detected.

The total magnet coil consists of 4 sections. The series connection between these sections is brought to the outside via simple, non-cooled safety leads. External dump resistors are installed across each coil section. These resistors dissipate a portion of the magnet's stored energy. This system is safer than one external dump resistor between the power leads, because an open circuit, developing inside the magnet, will not interrupt the ampere turns required to maintain the instantaneous magnet flux. The current will simply transfer to the active coil windings, due to the transformer action of the magnet. Multiple external dump resistors also allow better control of the maximum voltage excursions within the coil. The electrical parameters of the magnet are listed below:

$L = 16$ H

$B = 42$ KG at 210 A

$I = 210$ A max. (75% of short sample)

$E = \frac{1}{2}Li^2 \sim 350$ KJoules

Power lead current rating: 500 A

"Coffee leads" by American Magnetics, Inc.

Max. permissable power lead voltage drop: 200×10^{-3} V at 500 A

Max. permissable magnet voltage across terminals and to ground: 1000 V momentary

Note: Parameters are different than in reference 1), due to the addition of iron.

The magnet power leads are installed between the outside and the cryogenic environment of the coil. These leads are therefore purposely made thin. They have a number of small-diameter longitudinal cooling holes. Helium gas flows from the magnet through these holes to the warm gas return line, while cooling the leads. The magnet power leads might get damaged from over-heating, should the cooling passages get blocked. Lead over-voltage detectors are therefore installed at each magnet lead. The energy dump resistors are automatically activated via the quench switch, when the lead voltage drop exceeds a preset level. This assures fast turn-off of the magnet.

3. Description of the magnet power supply

The magnet power supply is rated 300 ADC at 7.5, 15 or 30 VDC[2]. Output voltages can be manually selected by means of secondary transformer taps. The current-regulated power supply uses secondary SCR's in a six-phase star configuration, with a freewheeling diode across the output. There are no ripple reduction filters at the DC output.

The unit is forced-air cooled and is fed from a 480 V, 3ϕ line, via a 30 Amp. circuit breaker. The power supply also contains the quench switch and lead over-voltage detectors. The heater power supply is external of the magnet supply, but could be installed as an integral part of future power supplies.

4. Basic Quench Protection

Figure 1 shows the basic quench protection and magnet power circuit, used for the superconducting magnet.

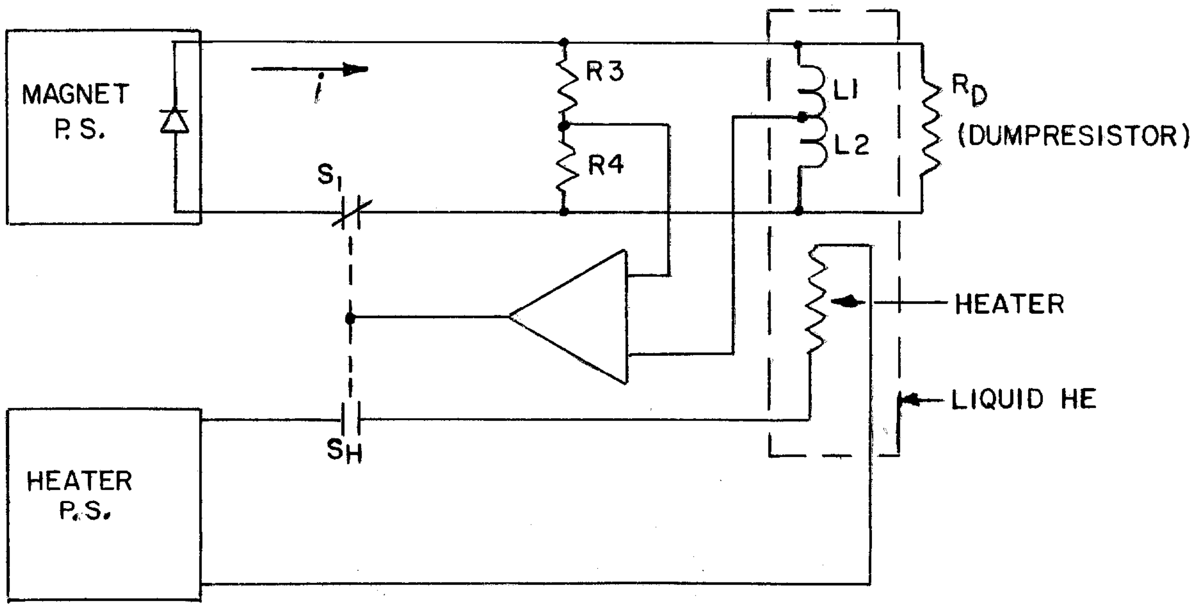


Figure 1

Basic Quench Protection

During normal operation switch S_1 is closed and the heater switch S_H is open. The input voltage across the superconducting magnet is 0 volts when i is constant and equals $L \frac{di}{dt}$ (R_D neglected) during charging.

The quench imbalance-detector bridge is balanced when: $\omega L_1 R_4 = \omega L_2 R_3$. Thus, with proper adjustment of R_4, the input to the bridge amplifier will remain 0 volts while the magnet charges. L_1 and L_2 represent the top and bottom half of the magnet coil. The safety lead attached to the center of the magnet coil is used with the bridge. R_3 and R_4 are externally-mounted resistors.

When a quench develops, a small part of the magnet coil becomes resistive, which imbalances the bridge. (fig. 2)

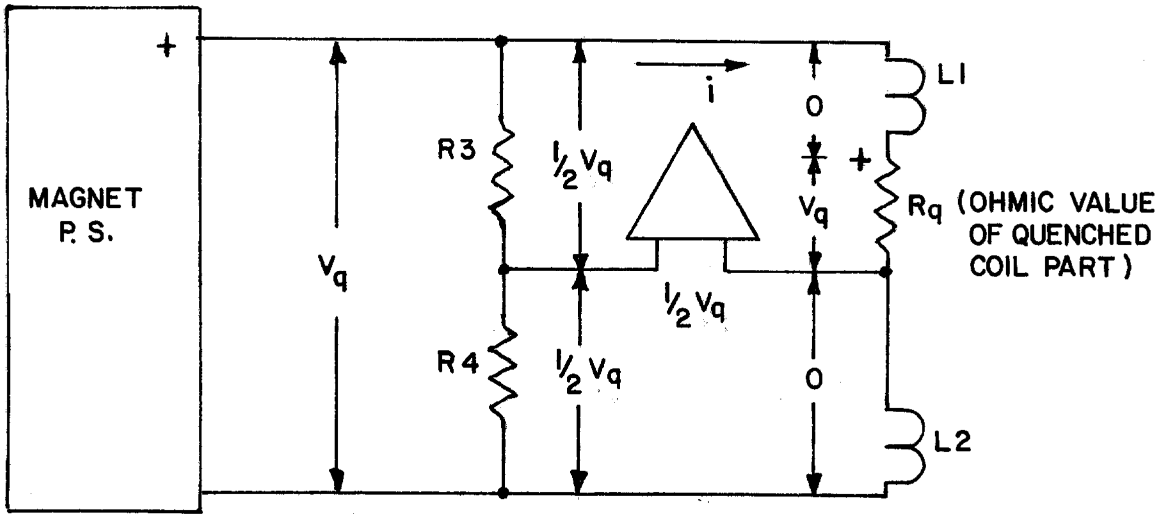


Figure 2

The magnet power supply will try to maintain a constant current during a quench. It will therefore supply a voltage V_q to overcome the voltage drop across the quenched section $V_q = iR_q$. The bridge amplifier sees $\frac{1}{2}V_q$ across its input. This imbalance signal is compared to a preset reference (trip) level. Exceeding the trip level opens S_1 permanently and closes S_H (fig. 1). S_H opens itself again via the heater control circuits, after a few seconds have elapsed. Opening S_1 disconnects the power supply from the magnet. However, the stored energy in the magnet will try to maintain the same current. This can only take place through the energy dump resistor, which is in parallel with the magnet. The magnet polarity will reverse and rise to a value: $V = iR_D \leq 1000$ V (momentary insulation rating). Thus, for i = 250 A, it follows that $R_D \leq 4\ \Omega$. Making R_D much smaller means that a larger fraction of the stored energy is dissipated in the cryogenic environment of the magnet coil.

The heater assures, by promoting large coil areas to quench, that not too much energy is dissipated in a small coil area, which may cause local overheating. The dump resistor dissipates a reasonable amount of the stored energy outside.

4.1. Construction of the quench switch

Previously-discussed figure 1 shows a very simple quench switch using mechanical contacts. Voltage and current ratings are, however, such that it is more economical to use SCR's to do the job.

Attached drawing #ATV022180 shows the used quench switch in detail. The switch is rated for 300 A, 1000 V, and is aircooled. We have to bear in mind that any circuit physically connected to the magnet has to be able to withstand 1000 V to ground. The upper half of the drawing shows the bridge imbalance detector, which senses a magnet imbalance via isolation resistors mounted at the magnet. These resistors are installed at the magnet for safety reasons.

Switch S_{1A} permits preliminary balance adjustments without running the power supply.

The inner and outer coil sections of the magnet have different turns with approximately an 8 to 10 ratio. It happened that the bridge "center" tap was installed at the series connection between two inner and two outer coils. Bridge balance, independent of the frequency, can only be obtained by giving the dump resistors ratios equal to the induced voltages in the coil sections of the bridge circuit. The ratio of the dump resistors must therefore be about the same as the turns ratios of the coil sections and depends on how the coils are laid in the magnet. Adjusting two of the dump resistors to 0.8 Ω gives satisfactory balance during start-up. We see, from the drawing, that an imbalance voltage enters the isolation amplifier (PC#1). PC#2 contains the signal rectifier (558), and the comparator (741). It produces four isolated output pulses at PT1 and PT2 when the signal level exceeds the trip level. PC#2 will also fire, when the inverting input of the comparator is made to go negative by closing a contact across 2/9 and 2/7. A temporary contact closure derived from the on/off relay (drawing #ATV021180) of the power supply is used for this function. Thus, any interlock trip, unrelated to magnet imbalance, will also fire the quench switch. The four isolated pulses from PC#2 have different functions. Two pulses have "outside quench switch" functions. They fire the heater P.S. and block the main P.S. SCR's.

The two other pulses are used "inside" the quench switch controls. One fires S4, which shorts the output from the 5 V and 10 V gate power supplies for S1. A negative voltage develops at S1 gate as soon as S4 is on (PC3). Of course, making the gate of S1 negative will not turn the DC current through S1 off. S1 needs also to have a reverse voltage for a period longer than its turn-off time t_q. This reverse bias voltage is supplied from pre-charged capacitor C1, and appears at the instant S3 fires from the remaining pulse of PC#2. C1 discharges and voltage sense relay K1 drops out. This drops the power supply summation string and also removes the reverse bias from S1 gate via T1. SCR4 will thus automatically resume a blocking condition. S1 is now off. The magnet current will now continue to flow through the dump resistors and through C1, via S3. C1 will charge in reverse to a voltage equal to iR_D. S3 shuts off automatically when the magnet current decays to zero. The "quench-charge ready" power supply at T2 tries to maintain the current through S3 via the magnet and the magnet power supply bypass diode, but is current-limited via two 1KΩ resistors. This current is smaller than the minimum holding current required for S3. Another function of the current-limiting resistors is to reduce the current through the "quench-charge ready" power supply diodes, when C1 is charged in reverse.

At this point in time the quench protection has done its job. The "quench-charge ready" power supply will again charge C1 in the proper direction. K1 picks up, when there is sufficient charge at C1, which permits gate power to S1, and a "quench-charge ready" permit to the magnet power supply.

The minimum size of C1 depends on the magnet current i, the turn-off time t_q of SCR S1, and the charge voltage of C1.

$$Q = CV$$

$$i = \frac{dQ}{dt} = C\,\frac{dV}{dt}$$

For $t_q = dt$ we can write: $it_q = C\,dV$

or: $C = \frac{it_q}{dV}$

The magnet current stays practically constant during the time that C_1 discharges. Say that:

$i = 300$ Amp

$t_q = 60 \times 10^{-6}$ sec. (turn-off time of SCR#470PB170)

$dV = 150$ V (charge voltage of C1)

Then we find:

$$C_1 = \frac{300 \times 60 \times 10^{-6}}{150}$$

$C_1 = 120\mu F$ (minimum required)

A safety factor of about 4 is used in this design, to take care of currents running through the dump resistors and the charging of stray capacitances. Selecting an SCR with a short turn-off time allows the use of a smaller capacitor C1. Typical turn-off times for most SCR's are 50×10^{-6} to 100×10^{-6} seconds. Relay K3 provides automatic discharge of C1 via door interlocks, for personnel safety. Loss of the $\pm$ 15 VDC power supply would go unnoticed and render the quench switch inoperative. Relay K2 is therefore installed and interlocked to the P.S. permit string.

4.2. Description of the dump resistors

The dump resistors must be able to dissipate most of the stored energy in the magnet without melting. The ohmic value is limited by the maximum permissable voltage across the magnet terminals, which is about 1000 V. A magnet running at 250 A would limit the dump resistor to $\frac{1000}{250} = 4\Omega$ maximum. The amount (weight) of steel in the dump resistors determines how much heat can be dissipated safely. The specific heat of steel is $c \approx 500$ Joules/^{0}CKG, which means that it takes 500 Joules to raise 1 KG of steel 1^0 C.

The stored energy in the magnet is $\frac{1}{2}Li^2 = \frac{1}{2} \times 16 \times 210^2 = 353 \times 10^3$ Joules. If ΔT is the permissable temperature rise of the steel in ^{0}C, we find for the weight W:

$$W = \frac{\frac{1}{2}Li^2}{c\ \Delta T} \text{ KG}$$

$\frac{1}{2}Li^2$ in Joules

c in Joules/^{0}C Kg

ΔT in ^{0}C

Allowing $\Delta T = 200^0C$ gives:

$$W = \frac{353 \times 10^3}{500 \times 200} \approx 3.5 \text{ Kg minimum}$$

It is assumed that all stored energy of the magnet is dissipated in the dump resistors, which is not the case. The energy dump resistors that have been installed are edge-wound, industrial-power resistors, of 1Ω each (Westinghouse #R20SE1D00). They have a temperature rise rating of 375^0C. One such resistor has been installed across each of the four coil sections.

5. The lead over-voltage detector

The lead over-voltage detector is show on drawing #ATV020180. The lead voltage is sensed via limiting resistors at the magnet, since the magnet will develop about 1000 V during a quench. The lead voltage is amplified (45J), rectified (558) and compared to a reference at 741. Lead voltages exceeding the reference level trip the power supply via relays K1. The lead voltage detector is built into the power supply.

6. The heater power supply

We have used an EMI power supply for the heater as shown in drawing #ATV020880. This power supply is resistance-programmed to a pre-set level of about 70 VDC from 1/7 and 1/8. Opening and closing relay contact K1-1 makes the heater power supply output go on and off.

Relay K1 is normally picked up, which makes the heater supply sit at about 70 VDC output. The output voltage level is adjustable by means of the potentiometer across 1/7 and 1/8. When the quench switch sends a firing pulse to the heater controls, it fires the series SCR S_H via the heater controls. The heater current then flows through the heater strips in the magnet. At the same time, the heater controls send a pulse to open a pressure relief (ROSS) valve at the magnet.

After 0 to 2 seconds (adjustable) have elapsed, relay K1 drops out, which makes the reference to the EMI heater supply go to 0 volts. The heater current decays to zero and S_H goes off. The heater pulse is now over.

Should the heater stay on for some reason, then the "heater on overtime" relays K3, K4 will trip the AC feed to the heater supply via 2/8 and 2/9, after 4 seconds have elapsed.

K2 is a heater-ready sense relay, which makes sure that the magnet power supply cannot start without the heater voltage being at the proper D.C. level. K2 in interlocked to the magnet power supply "permit interlocks" via 2/1 and 2/2.

The heater power supply is external of the magnet power supply. A simpler and less expensive heater power supply, consisting of a contactor, a transformer with taps and secondary diodes, could be used for future applications.

This supply and its control could be built into the magnet power supply.

7. Interlock flow diagram

Attached Fig. 3 shows the interlock flow diagram. This flow diagram is self-explanatory after the preceding text has been read.

Wiring plan drawing #ATV012880 shows most of the interconnections between the equipment.

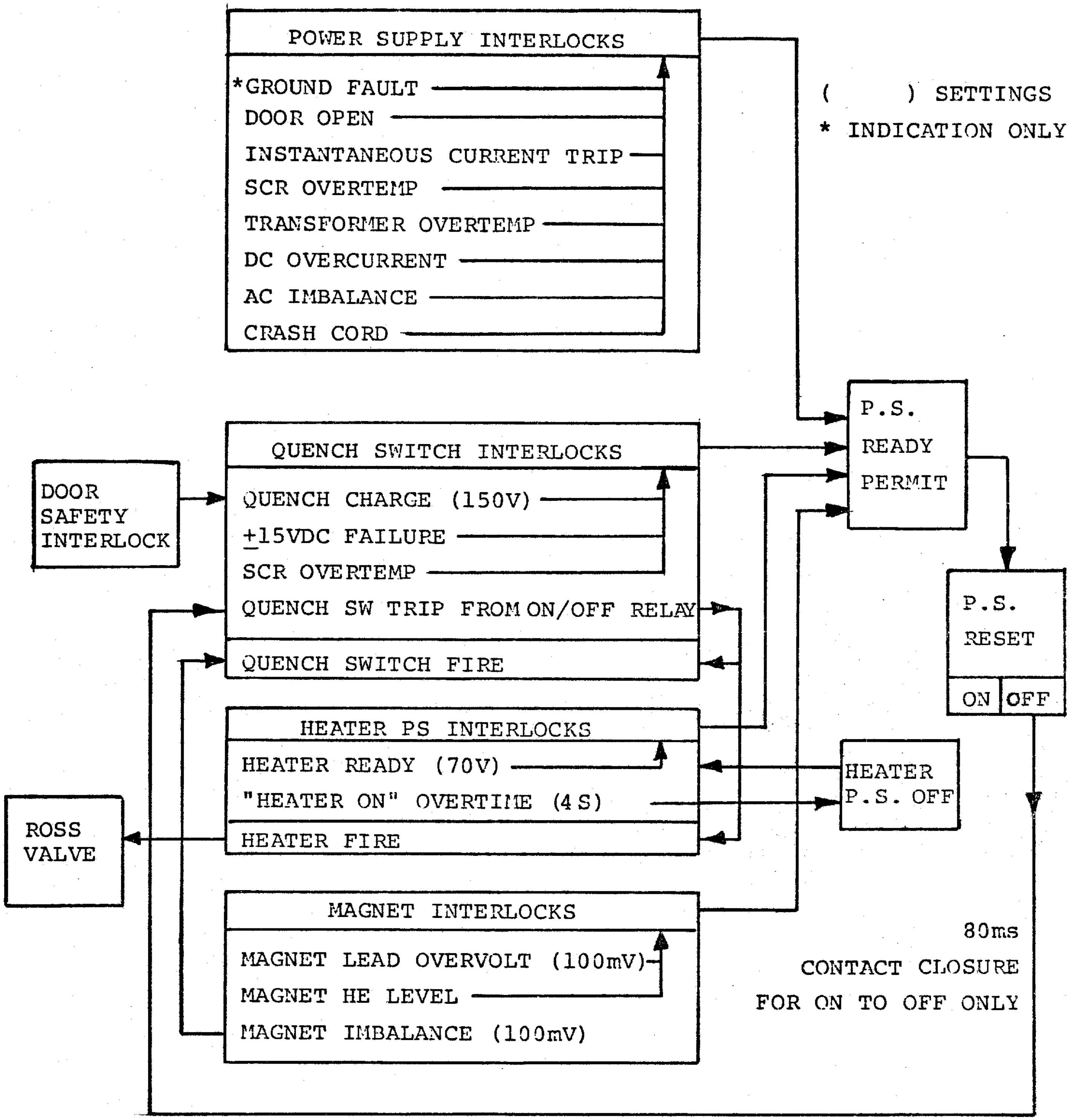
Acknowledgements

I wish to acknowledge the many constructive ideas generated by Senior Technicians Walt Jaskierny and Robert Innes. They assembled and tested the many circuits, and made them into a reliable operating system. Fred Rittgarn and his crew installed the electrical equipment at the site.

References

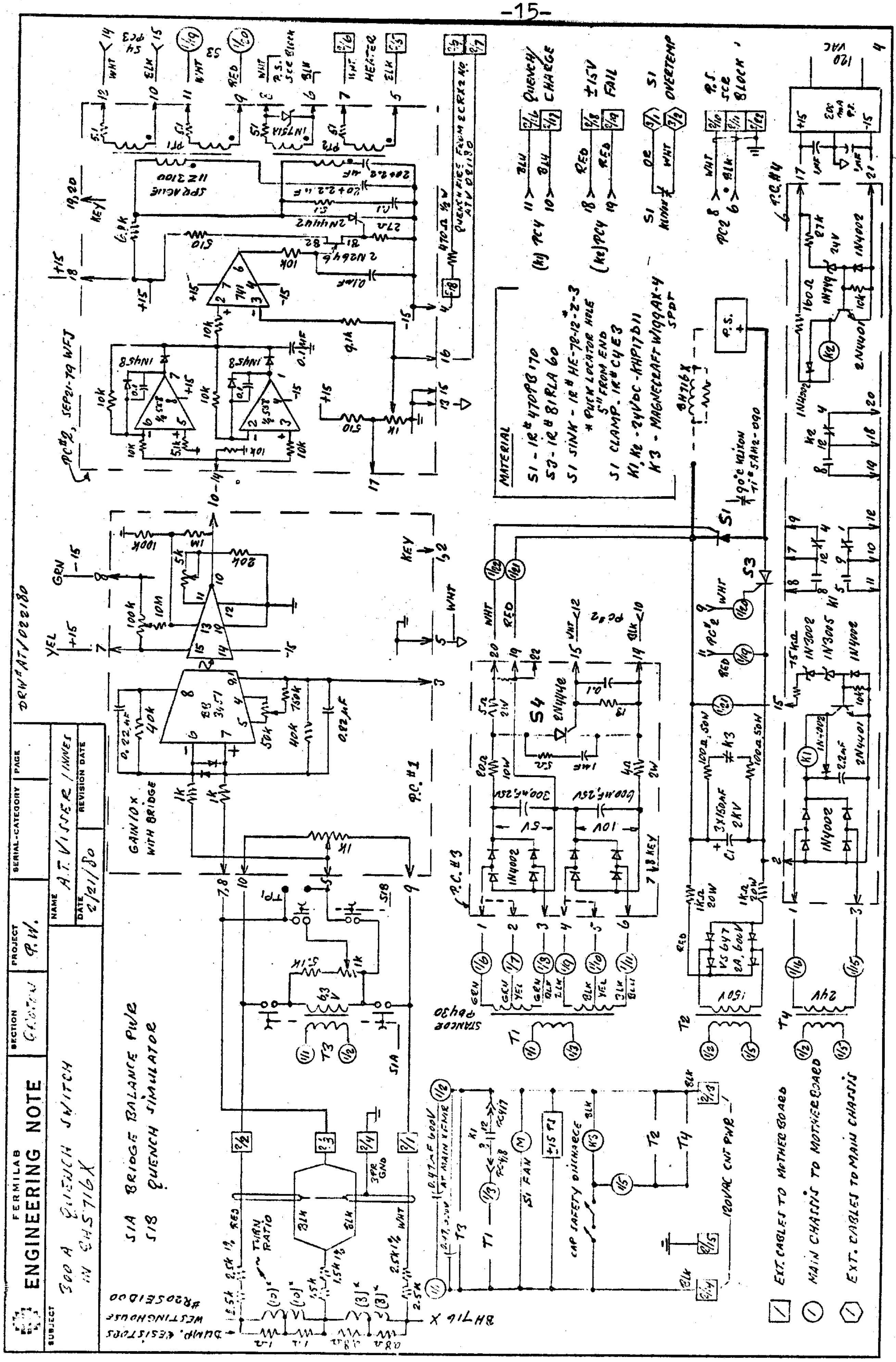
1. B. Cox, et al. "Design, Fabrication and Performance of Low-Current Superconducting Beam Line Dipole," TEEE Transactions on magnetics, vol. Mag. 15, no. 1, January 1979, pages 176, 177, and TM 882.

2. A. T. Visser, 3/24/76, FNAL Specification Spec. no. 6062-ES44030 for a 9 KW programmable D.C. power supply, type 9-0.3 for superconducting magnets at FNAL.



INTERLOCK FLOW DIAGRAM

FIGURE 3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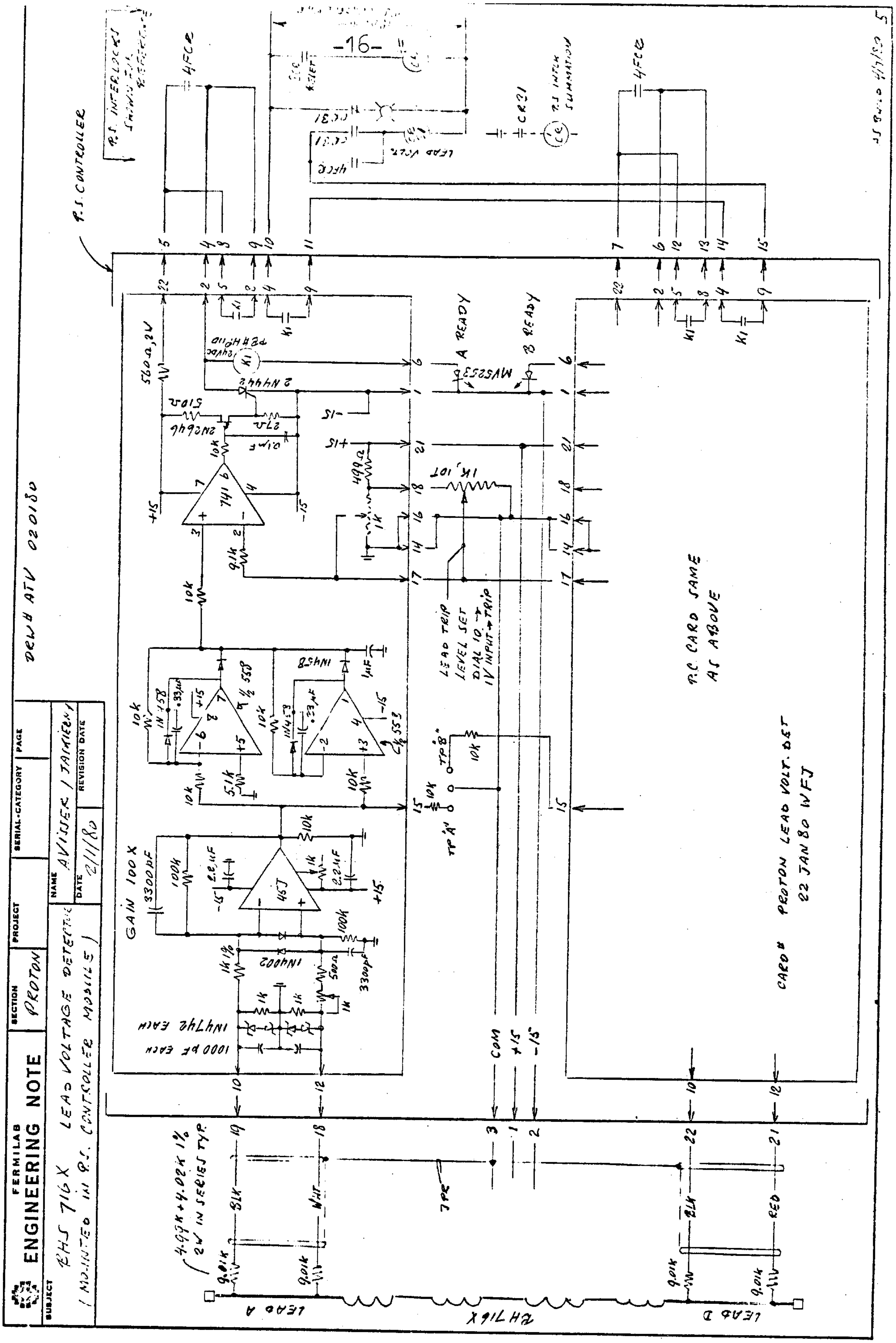
ENGINEERING NOTE
300 A QUENCH SWITCH
IN 8H716X
S1A BRIDGE BALANCE PWR
S1B QUENCH SIMULATOR
A.T. VISSER / INNES
2/21/80
DRW# ATV 022180
GAIN 10X WITH BRIDGE
P.C. #1
P.C. #2
P.C. #3
P.C. #4
MATERIAL
QUENCH/CHARGE
±15V FAIL
S1 OVERTEMP
EXT. CABLES TO MOTHER BOARD
MAIN CHASSIS TO MOTHER BOARD
EXT. CABLES TO MAIN CHASSIS
120VAC CNT PWR
CAP SAFETY DISCHARGE
DUMP RESISTORS
WESTINGHOUSE
TURN RATIO
SPRAGUE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ENGINEERING NOTE
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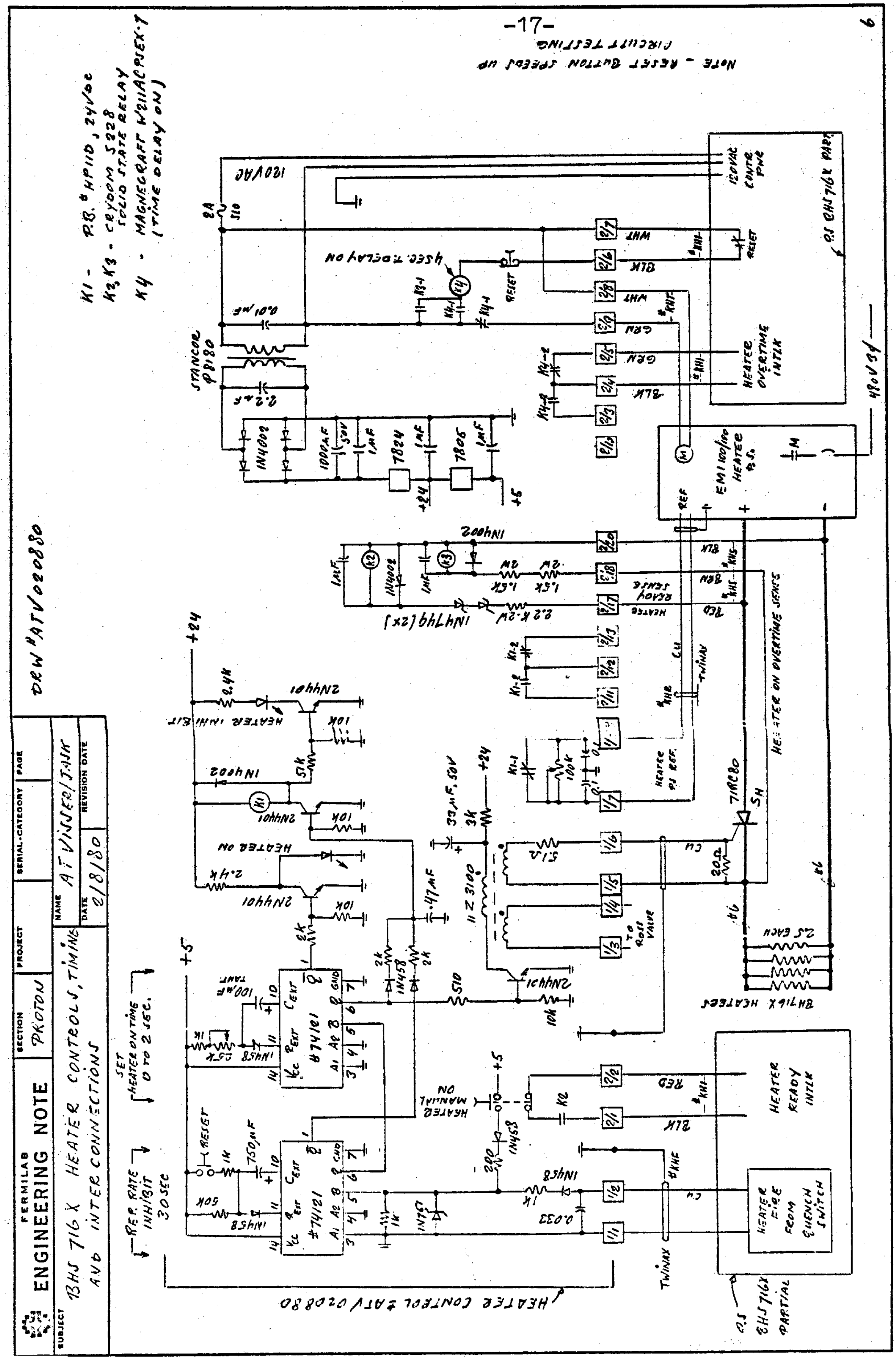
PROTON
RHS 716X LEAD VOLTAGE DETECTOR
(MOUNTED IN P.S. CONTROLLER MODULE)
DATE 2/1/80
DRWN ATV 020180
P.S. CONTROLLER
P.S. INTERLOCKS SHOWN FOR REFERENCE
4FCR
CR31
A READY
B READY
MV5253
2N4446
2N2646
741
GAIN 100X
453
1N4002
1N4742 EACH
1000 pF EACH
LEAD TRIP LEVEL SET DIAL 10 → 1V INPUT → TRIP
P.C. CARD SAME AS ABOVE
CARD # PROTON LEAD VOLT. DET 22 JAN 80 WFJ
COM
+15
-15
4.09K + 4.02K 1% 2W IN SERIES TYP.
BLK
WHT
RED
LEAD A
LEAD B
RH 716X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SECTION PROTON
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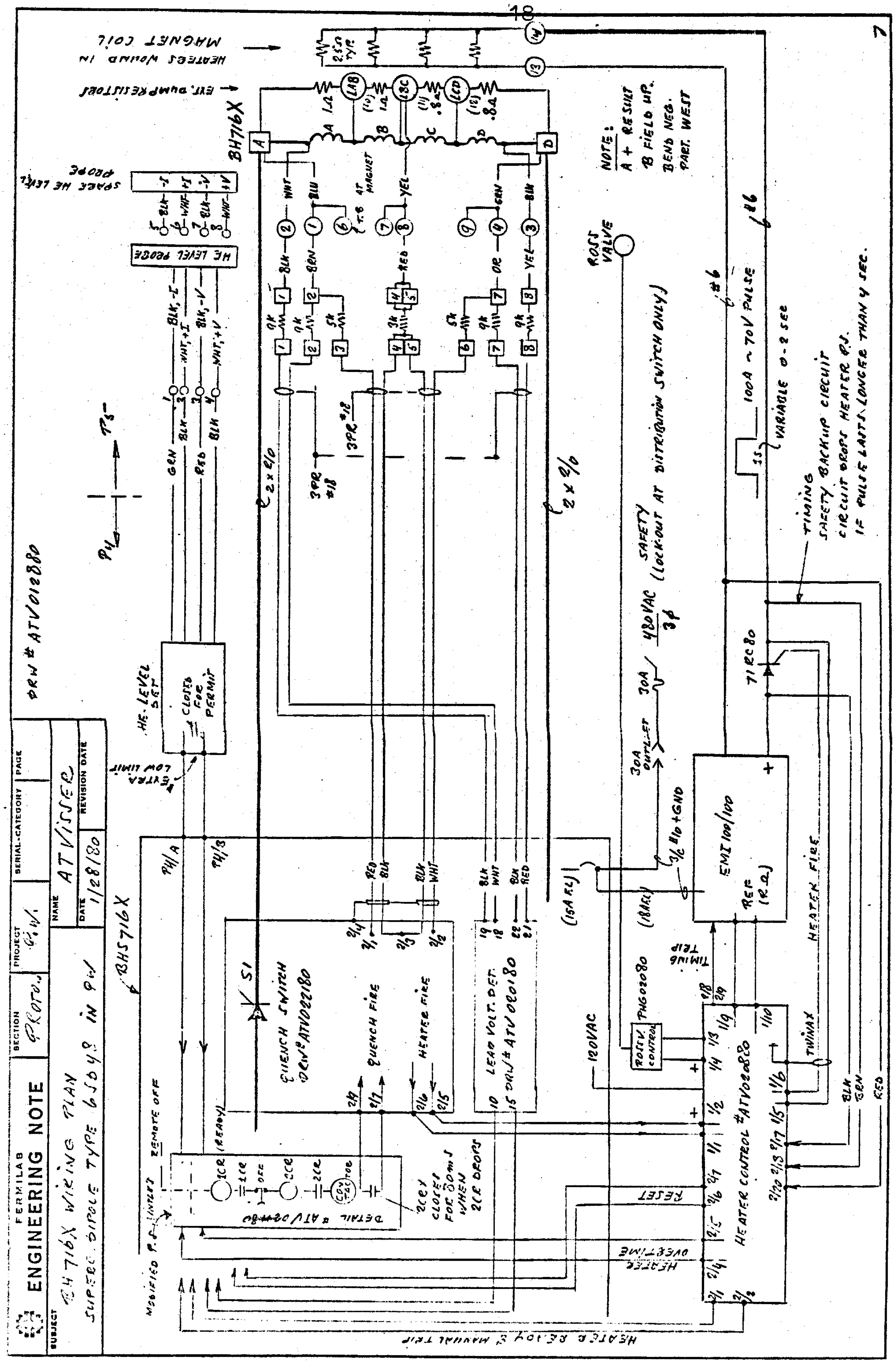
NAME AT VISSER/JAIN
DATE 2/8/80
DRW #ATV020880
-17-
NOTE - RESET BUTTON SPEEDS UP CIRCUIT TESTING
K1 - P.B. #HP11D, 24VDC
K2,K3 - CRYDOM S228 SOLID STATE RELAY
K4 - MAGNECRAFT W211ACPSX-1 (TIME DELAY ON)
HEATER CONTROL #ATV020880
REP. RATE INHIBIT 30 SEC
SET HEATER ON TIME 0 TO 2 SEC.
BHS 716X HEATERS
HEATER FIRE FROM QUENCH SWITCH
HEATER READY INTLK
HEATER OVERTIME INTLK
HEATER ON OVERTIME SENSE
EMI 100/100 HEATER P.S.
120VAC CONTR PWR
120VAC
480V 3φ
O.S. BHS 716X PART.
O.S. BHS 716X PARTIAL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HEATER CONTROL #ATV020880
EMI 100/100
QUENCH SWITCH
HE LEVEL PROBE
MAGNET COIL

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	DATE: 2/11/80	REVISION DATE		

DRW.# ATV 021180